A small, heated roost facilitates nursery establishment and increases the size of a lesser horseshoe bat (*Rhinolophus hipposideros*) colony in the northern Swiss Alps

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SUMMARY

Small thermal roofs in building attics might be a promising option to maintain and support nursery colonies of bats, but little empirical evidence is available. In a controlled study conducted from 2014 to 2021 on the northern side of the Swiss Alps, we investigated the effects of a thermal roof within an attic on the establishment and size of a nursery of lesser horseshoe bats *Rhinolophus hipposideros*. We installed a gable roof as a thermal roof (1.4 m^2 of usable roosting area with two internal heating mats) in the attic of a building that previously did not host a bat colony, monitored the temperature and later counted the number of roosting bats. The building is near a power station that hosted lesser horseshoe bats but which was shut down and becoming too cool to support a nursery colony of this species. The ridge of the thermal roof had a temperature of about 33°C, while the temperature in the building's sub-roof was lower on average and subject to greater temporal fluctuations. Two years after installation, the bats started to use the roost consistently in summer and the numbers grew from 22 in 2014 to 239 in 2021. During 136 survey days we found that 85% of the bats were roosting in the small thermal roof, and only a minority were in the much larger sub-roof suggesting that the former was preferred. Our study provides empirical evidence that a thermal roof can initiate the colonisation of a replacement roost and support colony growth.

BACKGROUND

In many European countries, including Switzerland, populations of the lesser horseshoe bat *Rhinolophus hipposideros* declined sharply from the 1960s to the late 1980s (Bontadina *et al*. 2000). Since the late 1990s, populations have been increasing and slowly spreading at least on the northern side of the Swiss Alps (Bontadina *et al*. 2006, own data). However, this species is classified as endangered on the Red List of Switzerland (Bohnenstengel *et al*. 2014) and conservation measures to increase its populations are still required. Thermal optimisation of nurseries could be a suitable conservation strategy that may help strengthen existing nurseries and facilitate the population increase (Ransome 1998, Schofield 2008).

Pregnant and nursing bats try to maintain a constant body temperature above 35°C (normothermic state, Neuweiler 2000) so that the necessary metabolic processes run optimally and the growth of the embryo and milk production are not delayed. Pregnant and lactating bats try to keep the energy expenditure for thermoregulation as low as possible by selecting day roosts with minimal heat lost to the environment (Speakman & Thomas 2003). Ideally, all maternity roost sites are in the same building (complex) with different degrees of insulation from the outside temperature (e.g. heat-permeable sub-roof and thermally insulated interior) (Hamilton & Barclay 1994). This means that bats do not have to leave the building during the day when the outside temperature is changing, reducing the risk of predation. In temperate zones roost temperatures are often low even in summer. Reproducing females therefore form dense clusters at the roost such that heat loss is further reduced by a temperature exchange among females (Roverud & Chappell 1991, Ransome 1998).

Due to the heat exchange, there is a temperature range of the ambient air where a reproductive female has to expend a minimum of her own energy to maintain her normothermic body temperature (Geiser 2006). We chose the term "thermal comfort range of the nursery" (TCRN) for this specific temperature range, which takes into account the bats' behavioural adaptation to their thermal environment. The lower range of the TCRN corresponds to the temperature where an active (normothermic) bat no longer requires clustering while the upper range corresponds to the temperature at which a bat can no longer release its excess body heat to the environment and therefore leaves the roost site (Kayikcioglu & Zahn 2004).

Few publications deal with the optimisation or creation of new roosts for horseshoe bats (e.g. Freer *et al*. 1998, Kelleher & Marnell 2006, Schofield 2008) or address the problem of overheating of their roosts in hot summer weather (Kayikcioglu & Zahn 2004, Alcalde *et al*. 2017). Thermal optimisation of horseshoe bat nurseries has been created previously (Richarz 1989, Leitl 2021). A detailed study by Ransome (1998) found positive effects of heaters installed in maternity roosts of greater horseshoe bats (*R. ferrumequinum*), ensuring average temperatures of 27-29°C, on the growth and survival of young. However, the effectiveness of creating alternative bat roosts and the management of the microclimate of artificial bat roosts is still largely unknown (Sutherland *et al*. 2021). Here we try to fill this gap by quantifying the effectiveness of creating a new

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roost with thermal optimisation for a nursery of lesser horseshoe bats, hence highlighting a further potential positive aspect of thermal optimisation. We installed a small heated thermal roof in the attic to establish a spatially limited TCRN from spring to autumn and compared the number of bats using it and the rest of the sub-roof over the next seven years after construction.

ACTION

In 2003 a nursery colony of lesser horseshoe bats was discovered in the attic of the "EWR Energie AG" power station (EWR) (approx. 1 km south of Meiringen, 810 m a.s.l.; 46.71512 N, 8.18357 E, R in Figure 1). The EWR is located on a northeast exposed slope surrounded by a pattern of mixed forest and pastures (Figure 2). In September 2010, the EWR was shut down. As a result, no waste heat from the now decommissioned turbines reached the attic. As the owners of the power plant were considering demolishing the building, an alternative nursery roost needed to be established. The number of recorded adult (≥ 1 year old) lesser horseshoe bats in the attic of the EWR power station, is summarised in Table 1.

The mountain station of the Reichenbachfallbahn (RBB), located 50 m south of the EWR (Figure 2), was a potential alternative but the attic was not accessible to horseshoe bats. Moreover, depending on the wind direction, water from the nearby Reichenbach Falls sprayed onto the roof. We assumed that the evaporation of the water cooled the roof surface and lowered the air temperature in the attic. This building could therefore only become a nursery after structural adjustments.

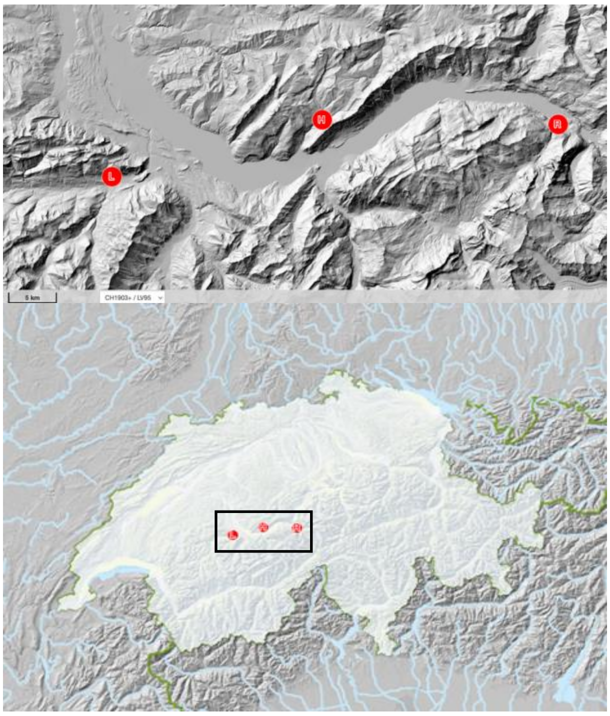

Figure 1. Geographical location (upper map) of the study sites within Switzerland (lower map) and nursery roosts mentioned in the text. L: Latterbach (left on the upper map); H: Habkern; R: Reichenbach (EWR, RBB; right on the upper map). Source: https://map.geo.admin.ch

Table 1. Recorded adult lesser horseshoe bats in the attic of the EWR power station. Counts were carried out once a year, between mid-June and mid-July. NA: no data available.

Year	number of recorded adult bats
2003	33
2004	≥ 30
2005	NA
2006	≥ 53
2007	NA
2008	13
2009	15
2010	NA
2011	NA
2012	0
2013	≥ 11
2017	0
2018	0
2019	NA
2020	NA
2021	0

Figure 2. View of the EWR (Schattenhalb 2) power station on the right (original nursery site of lesser horseshoe bats) and on the left the funicular mountain station of the Reichenbachfall-Bahn (RBB; compensation nursery site where the thermal roof was installed).

Construction work:

In April 2012 we created a 40 x 20 cm entrance opening in the wooden wall on the north-west exposed side of the RBB at a height of 2.9 m. At the same time, we installed an electrically heated gable roof (100 cm eaves length; 145 cm side width; 75 cm gable height), hereafter called a thermal roof (THR), 2.8 m above the attic floor on the underside of the roof (Figure 3a & b). The thermal roof was raised or lowered on a steel cable over a pulley for maintenance and cleaning.

The thermal roof was made of 3-layer spruce wood boards. An electric heating mat (AEG Haustechnik; TBG 105, dimensions 55 x 75 cm; weight 2 kg; 230 V / 105 W; IP X7) was attached to each of the two undersides of the gable roof (plywood panels). On both sides of the heating mats (perpendicular to the ridge) two wooden strips were screwed on as spacers. A semi-rigid fibreglass

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net (≤ 1 mm mesh size), to which the bats could cling, was attached to outer wooden strips running all around. The fibreglass net was approximately 3 cm from the heating mats so that the bats would not come into contact with the mats (Figure 3b).

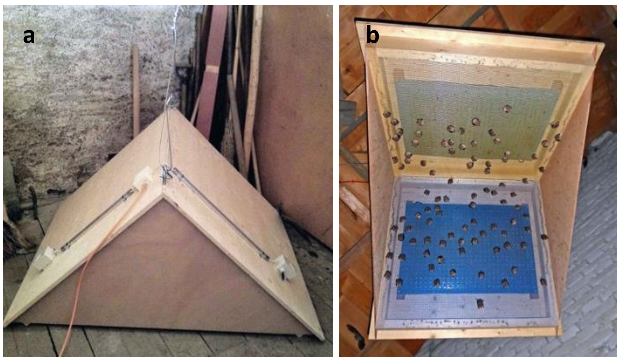

Figure 3a. The thermal roof on the floor of the attic with the two thermostats at the bottom of each of the two sloping sides. At the ridge of the roof the two suspensions are fixed with steel cables. **3b.** Underside of the thermal roof with roosting lesser horseshoe bats. The two blue heating mats lie approx. 3 cm behind the semi-rigid fibreglass net. This is mounted on wooden strips which serve as spacers to the heating mats.

To set the ridge temperature in the THR, we first followed data of Richarz (1989) and Freer *et al.* (1998). We then measured temperature (using iButton® DS1922L-F5#; Maxim Integrated Products Inc.) in nursery roosts with over a hundred lesser horseshoe bats in the Bernese Oberland in summer 2011 which showed hourly peaks in the range of 30°C to 35°C between June and August. Due to the cooling of the roof of the RBB by the spray from the waterfall, we decided to set the thermostats (Trafag; Ministat M/MS 624/634; www.trafag.com; sensor located in the ridge of the THR) for the two heating mats ensuring an air temperature between 32°C and 34°C in the ridge of the THR.

Camera and temperature monitoring from May to September 2013 in a maternity roost in Latterbach (Figure 1) revealed that clustering of pregnant and nursing bats occurred in temperatures up to c. 23°C and that the roost was abandoned above c. 33°C. This was confirmed during further camera and temperature observations from May to September 2021 in nursery roosts in Latterbach and Habkern (Fig. 1). Based on these observations, we assumed that the thermal comfort range of a lesser horseshoe bat nursery (TCRN) on the north side of the Swiss Alps is c. 23° to 33°C.

Measurement of the air temperatures at roost sites

From 20 May to 31 August 2011 air temperatures were measured hourly simultaneously under the roof of the potential new roost (RBB) and in the old roost (EWR) using iButton® DS1922L-F5# (Maxim Integrated Products Inc). We also measured the temperature in the ridge of the thermal roof from May 20 to August 31 2012 (see Table 2, Figure 4).

Table 2. Summary statistics of hourly temperature measurements (in °C) from 20 May to 31 August (2011 and 2012 respectively) in the attics of EWR power station (ridge in the sub-roof of the old roost), RBB mountain station (ridge in the sub-roof of the replacement roost) and in the ridge of the thermal roof (THR) inside the RBB attic.

	EWR ridge (2011)	RRB ridge (2011)	THR ridge (2012)
Number of measurements	2,496	2,496	2,496
Minimum	8.1 °C	12.7 °C	31.6 °C
Maximum	41.6 °C	30.2 °C	34.6 °C
Range	33.5 °C	17.5 °C	3.0 °C
Median	17.6 °C	19.2 °C	33.1 °C

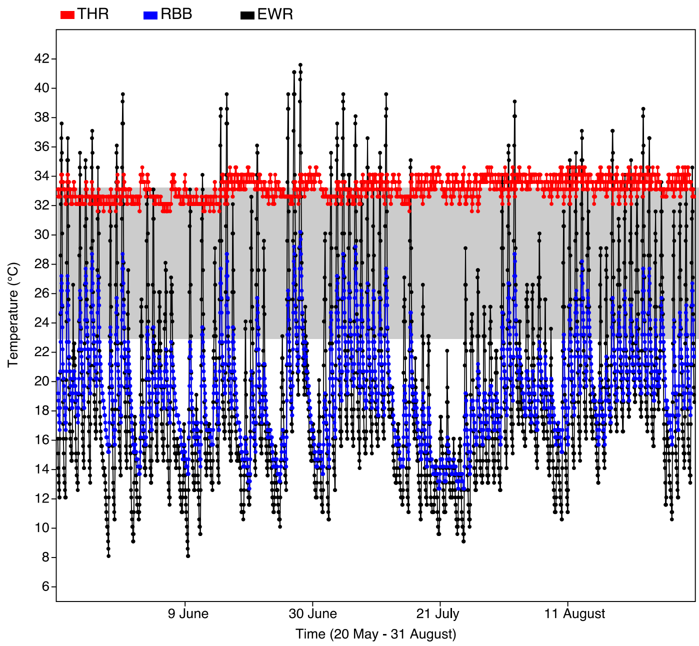

Figure 4. Hourly temperatures (in °C) from 20 May to 31 August 2011 (black = EWR sub-roof ridge; blue = RBB sub-roof ridge) and from 20 May to 31 August 2012 (red = THR ridge). The dots correspond to the measured values; the lines connect successive values. The grey shaded area shows the thermal comfort range of the nursery (TCRN) for lesser horseshoe bats on the north side of the Alps in Switzerland as defined in the text.

Spreading of droppings and relocation of lesser horseshoe bats

As no lesser horseshoe bats were detected in the thermal roof in 2012, we collected droppings from the old roost in EWR in May 2013 and spread them on a plastic sheet under the thermal roof with the intention of attracting bats to the new roost (Richarz 1989).

On 5 July 2013 eight males and one female lesser horseshoe bats were trapped during daytime from a nearby (1.3 km distance) summer colony that hosted 17 individuals. The nine bats were immediately released into the RBB attic with the operating thermal roof. On 12

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July 2013 we caught four females in the attic of the EWR and released them the same day in the attic of the RBB.

Monitoring

Until the end of 2012 there were no new bat droppings on the plastic sheeting under the thermal roof, suggesting that it was not yet being used by lesser horseshoe bats as a roost. In 2013, only two bats were seen in the thermal roof on 5.7.2013 and 12.7.2013, before the captured lesser horseshoe bats were released on the same days. Since 2014, the RBB attic has been regularly used as a nursery roost. From July 2014 until 2021 the number of bats in the thermal roof and in the building's sub-roof was counted once per week from mid-May to the end of September.

Costs (from 2011 to the end of 2014)

Carpenter costs €1,500 (material: €600; salary: €900), electrician costs €2,600 (materials: €1,500; salary: €1,100). All costs included 8% VAT.

Additional costs of €9,000 over the period 2011-2014 were incurred for project coordination, planning, site management, capture and release of bats, monitoring and data evaluation by a biologist. These costs were exempt from VAT. Energy consumption was around 700 kWh/year (mid-April to mid-October; average (2011-2014) cost per kWh was about €0.24) and depended on the seasonal weather.

Analysis

The number of bats counted every week in the thermal roof and in the sub-roof in the RBB were analysed with generalized linear models in R (R Core Team 2018) using library MASS (Venables and Ripley 2002). The models had a negative binomial error distribution and included interacting effects of location, year, and calendar week and its square. Location is categorical with two levels (thermal vs. sub-roof), year is categorical with seven levels (2014 to 2020), and calendar week and its square are continuous. We fitted nine models with different combinations of the explanatory variables and ranked them according to their support by the data (Table 3) using the Akaike Information Criterion (AIC).

CONSEQUENCES

From 20 May to 31 August 2011, the air temperatures in the attic ridge of the EWR and the RBB varied from 8°C to 42°C and from 13°C to 30°C, respectively (Table 2, Figure 4). The proportion of time that temperatures remained in the TCRN (23-33°C) of lesser horseshoe bats was 0.18 at the EWR and 0.11 at the unheated sub roof of the RBB. In contrast, the temperature in the thermal roof's ridge (20 May to 31 August 2012) only fluctuated between 32°C and 35°C and was therefore always within the TCRN.

The best model explaining the variation in the number of lesser horseshoe bats included location, year, week, and their interactions (Table 3); the parameter estimates of the best model are provided in Table 4. The number of individuals typically peaked in calendar weeks 28 to 30 and the majority of bats used the thermal roof (Figure. 5). Although the surface area of the thermal roof is much smaller than the sub-roof (1.4 m^2 vs. approx. 150 m^2), between 75-98% (100% = annual sum of all weekly counts) of the individuals used the thermal roof, clearly indicating a preference. The peak number of lesser horseshoe bats present on a census day has increased each year, from 24 in 2014 to 239 in 2021 (Table 5; all year effects were positive) corresponding to a mean annual increase of 39%.

Table 3. Selection of the negative binomial models for the count data. Given are the model deviance, the difference of the Akaike's Information Criterion of the current to the best model (ΔAIC) and the Akaike weights. Location (L) is categorical and has 2 levels (thermal vs. sub-roof), year (Y) is categorical and has 7 levels (2014 to 2020), and week^2 (W^2) is continuous. + indicates additive terms, x indicates interacting terms. Note that W^2 is an abbreviation for week + week x week.

Model	Deviance	ΔAIC	AIC weight
L	328.17	231.36	0.00
L + Y	329.57	114.61	0.00
L + Y + L x Y	325.13	76.77	0.00
L + W^2	329.11	208.45	0.00
L + W^2 + L x W^2	330.85	193.94	0.00
L + Y + W^2	333.94	82.22	0.00
L + Y + W^2 + L x Y	330.58	46.86	0.00
L + Y + W^2 + L x W^2	338.80	56.75	0.00
L + Y + W^2 + L x Y + L x W^2	332.19	0.00	1.00

Table 4. Parameter estimates, associated standard errors, z-values and the significance levels (*p*) of the parameters of the best negative binomial model as identified in Table 3. Note that the intercept refers to the location 'thermal' in year 2014. The location effect is the difference between 'thermal' and 'subroof' in year 2014, and the year effect is the difference between year 2014 and the year given in parentheses for the 'thermal'. L = location, Y = year, W = week, W2 = week + week x week.

Parameter	Estimate	Standard error	z-value	p
Intercept	-4.532	1.811	-2.502	< 0.05
L	-9.647	2.972	-3.246	< 0.001
W	0.559	0.123	4.547	< 0.001
W^2	-0.010	0.002	-4.768	< 0.001
Y (2015)	0.108	0.287	0.377	0.706
Y (2016)	0.611	0.301	2.029	< 0.05
Y (2017)	0.982	0.293	3.354	< 0.001
Y (2018)	1.221	0.285	4.288	< 0.001
Y (2019)	1.289	0.285	4.532	< 0.001
Y (2020)	1.702	0.289	5.895	< 0.001
Y (2021)	1.525	0.286	5.329	< 0.001
L x Y (2015)	-0.085	0.655	-0.130	0.896
L x Y (2016)	0.822	0.610	1.349	0.177
L x Y (2017)	1.920	0.582	3.297	< 0.001
L x Y (2018)	2.502	0.570	4.390	< 0.001
L x Y (2019)	2.717	0.569	4.774	< 0.001
L x Y (2020)	1.799	0.574	3.134	< 0.005
L x Y (2021)	1.935	0.572	3.381	< 0.001
L x W	0.251	0.198	1.265	0.206
L x W^2	-0.002	0.003	-0.612	0.540

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During three checks (visual with spotlights and acoustic with a heterodyne detector tuned to 105 kHz) of the attics on 5 July 2017, 18 July 2018 and 23 July 2021, no lesser horseshoe bats were detected in the EWR (Table 1), while in the RBB 81, 130 and 165 individuals were counted on these days, respectively.

Table 5. Peak counts of lesser horseshoe bats in the nursery of the RBB mountain station (compensation roost with a thermal roof)

Year	Calendar week	Peak count
2014	32	24
2015	31	44
2016	29	67
2017	30	89
2018	25	134
2019	26	161
2020	27	219
2021	30	239

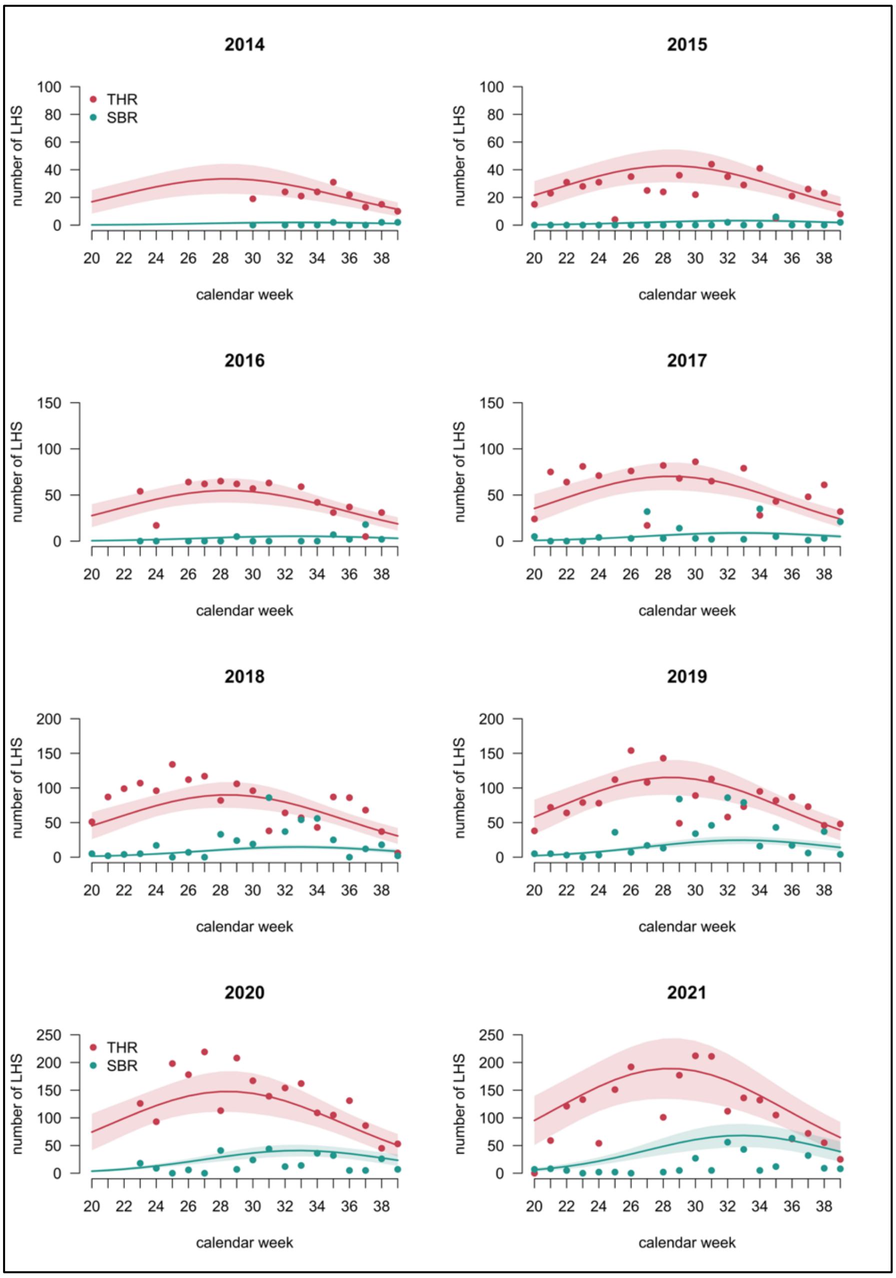

Figure 5. Annual and seasonal variation of the number of lesser horseshoe bats present in the attics of the RBB mountain station, either in the thermal roof (THR) or in the sub-roof (SBR). Dots show the weekly counts, the lines are predictions from the best generalized linear model with a negative binomial error distribution and including interacting effects of the year, calendar week and its square, and location (Table 3). The shaded areas show the range of the 95% confidence intervals of the predictions.

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DISCUSSION

Our study provides compelling evidence that the installation of a small, heated roof facilitated the development of a new nursery colony of lesser horseshoe bats and resulted in a strong increase in colony size. This suggests that installation of artificial thermal roofs, that maintain the temperature within an optimal range for bats, could be a promising management option to maintain and support populations of bats occupying roof voids of buildings (Ransome 1998).

The short distance of only 50 m between the old and new colony roost might have favoured colonisation. Relocation to a roost site outside the species' core sustenance zone of c. 2 km radius around the nursery of lesser horseshoe bats (Bontadina *et al.* 2002, BCT 2016) might be more difficult to realise, as reported (e.g. Weinberger *et al.* 2009).

Lesser horseshoe bats are long-lived (Jan *et al*. 2019) with an annual survival probability ~ 0.8 corresponding to a mean life expectancy of > 4 years. The maximum possible annual growth of a geographically closed population is likely to be less than 20% (Niel & Lebreton 2005) so, with an average of 39%, we recorded a much higher annual increase of the nursery population. This strongly suggests that immigration from other roosts in the vicinity has contributed to the observed growth rate of the colony which, in turn, supports installation of a thermal roof as an attractant.

In temperate latitudes (with cold periods, but also increasingly frequent heat waves during the summer months), lesser horseshoe bats prefer nurseries in buildings that provide roosting space at different temperatures (e.g. Kolb 1950, Gaisler 1963, Freer *et al*. 1998, Kayikcioglu & Zahn 2004, own observations). It is likely to be beneficial if only a relatively small area is thermally isolated and constantly heated to the upper limit of the TCRN, and if sufficient other areas in the same building that provide roosts with lower air temperatures are available, as Ransome (1998) also postulated for greater horseshoe bats.

We installed a thermal roof in 2018 (same type as in the RBB) in another nursery of lesser horseshoe bats in the Bernese Oberland. Here, between three and five greater horseshoe bats were also present and, up to 2020, were the only bats to use the thermal roof. In early 2021, we installed a second identical thermal roof a few metres away from the first one. Camera monitoring showed that the lesser horseshoe bats were now using the second thermal roof, while the greater horseshoe bats were mainly using first one. It is possible that greater and lesser horseshoe bats are intolerant of each other in their immediate roosting environment (Salinas-Ramos *et al*. 2020). Hence, if more than one species occurs in a roof void, interspecific interactions may be considered when heated roofs are offered.

There are a number of technical details for the construction and maintenance of artificial thermal roofs and we offer the following recommendations:

1. An ideal temperature in the ridge of the thermal roof seems to be the upper range of the TCRN (between 32° and 34°C in our case; Schofield 2008). Since the temperature decreases gradually from the ridge to the lower part of the thermal roof, the temperature sensor is best placed in the ridge. Furthermore, the thermal roof requires two side end walls to keep the emerging air exchange under the heating mats low.
2. The inclination of the heated surface of 45 degrees is a compromise between the two extremes of vertical roosting (with irradiation of a large area of the bat's body, but space for only a few individuals) and horizontal roosting site (with space for many individuals, but only a small directly irradiated area of the bats in each case). Vertical heated surfaces seem unsuitable because faeces may fall onto individuals hanging below or between the heating surface and the mesh.
3. The grid in front of the radiator is preferably made of non-combustible material and have a mesh size of no more than 1 mm so that the bats' feet or toes do not get caught in it.
4. It is advantageous to cover both underroof sides of the thermal roof (but not the vertical end walls) with radiant heaters that cover as much of the surface as possible. Heat is transferred to a distant bat in the air more quickly by radiation than by convection, which first heats the air and then the bat. Heat transfer by convection (air flowing past), may be important only during the times when the thermostat switches off the heating for a short time (to avoid overheating).
5. A gable roof with two heated sub-roof areas totalling 1.4 m^2 usable area (in vertical projection) was sufficient to create an adequate roost site area with a nursery thermal comfort range (TCRN) for c. 200 adults plus pups of lesser horseshoe bats. For larger colonies, two or more such thermal roofs may be needed.

We recommend that a thermal roof might be most useful as a tool to maintain and support lesser horseshoe bat nursery colonies in the following situations:

- When the daily duration of solar radiation on the nursery building is low, e.g. due to the surrounding landscape (mountains, trees, buildings, etc.).
- When unfavourable thermal changes have occurred in the building with the nursery (e.g. roof insulation, loss of waste heat in the building).
- When the nursery is located at the edge of the current regional distribution range.
- When a building with an existing nursery is about to be demolished. A thermal roof in a potential nearby replacement building could increase the attractiveness and speed up the relocation, as in the present case.

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